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THE INFLUENCE OF BANK STRENGTH ON CHANNEL GEOMETRY: AN INTEGRATED ANALYSIS OF SOME OBSERVATIONS

HE QING HUANG* and GERALD C. NANSON

School of Geosciences, University of Wollongong, New South Wales, 2522, Australia

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ABSTRACT

Bank strength exerts a significant influence on river channel geometry, but quantification of this relationship has been limited to only a few specific circumstances. This is due to both the complex nature of bank strength and the difficulty in incorporating its influence in river channel geometry relations. In order to undertake an integrated analysis of wide-ranging field observations, this study applies a recently developed multivariate model of channel geometry. When the banks of a number of laterally stable streams are categorized on the basis of the bank sediment and vegetation, the multivariate model yields numerical indices of bank strength. Within the range of the data analysed, bank strength can produce a three-fold change in channel width and a two-fold change in depth corresponding to about a 1·6-fold change in cross-sectional area. © 1998 John Wiley & Sons, Ltd.

KEY WORDS bank strength; river channel geometry; multivariate model; vegetation; sediment composition; numerical indices

INTRODUCTION

Many alluvial channels exhibit a transport-active bed and yet have relatively stable banks. In response to variations in strength (a function of bank sediment and vegetation), these banks differ in their resistance to erosive forces, and exert considerable influence on alluvial channel geometry. This is demonstrated clearly both in field studies (e.g. Blench, 1952; Simons and Albertson, 1960; Schumm, 1960, 1968; Ferguson, 1973; Knighton, 1974; Osterkamp and Hedman, 1982; Andrews, 1984; Hey and Thorne, 1986; Huang and Nanson, 1997) and in analytical modes (e.g. Osterkamp *et al*., 1983; Miller, 1984; Osman and Thorne, 1988; Ikeda and Izumi, 1990; Rhoads, 1991, 1992; Millar and Quick, 1993; Kilberg and Howard, 1995; Darby and Thorne, 1996). However, only a limited number of integrated studies have been conducted and most of them have applied either regional or complex models, making comparison of results difficult.

The purpose of this study is to undertake a uniform analysis of available wide-ranging field observations using a multivariate model of river channel geometry developed by Huang and Warner (1995). This model has physically incorporated the influence of bank strength and is believed to be of general use due to its success in illustrating the general form of river channel geometry and in interpreting the limitation of commonly applied bivariate models of downstream hydraulic geometry (Huang and Warner, 1995; Huang and Nanson, 1995; Huang, 1996). Because there are difficulties in providing accurate predictions of bank strength due to the complex and heterogenous nature of bank sediment and vegetation, this study examines field observations from rivers and canals where channels have been classified into several groups according to the character of their bank sediment and vegetation. The results appear logical and three numerical indices that reflect the influence of bank strength on channel width, depth and cross-sectional area are broadly defined.

* Correspondence to: H. Q. Huang, School of Geosciences, University of Wollongong, New South Wales, 2522, Australia.

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MODEL, METHOD AND DATA

A multivariate model of river channel geometry

In an examination of the applicability of a recently developed experimental flume relationship between channel shape and boundary shear distribution (Knight, 1981; Knight *et al*., 1984, 1994; Flintham and Carling, 1988) in alluvial channels, Huang and Warner (1995) proposed the following relations as the general form of river channel geometry:

$$W = C_W Q^{0 \cdot 5} n^{0 \cdot 355} S^{-0 \cdot 156} \tag{1}$$

$$D = C_D Q^{0 \cdot 3} n^{0 \cdot 383} S^{-0 \cdot 206} \tag{2}$$

$$A = C_A Q^{0 \cdot 8} n^{0 \cdot 738} S^{-0 \cdot 362} \tag{3}$$

where W, D, A, Q, n and S represent channel width, depth, cross-sectional area, flow discharge, channel average roughness and slope, respectively. When the coefficients C_W, C_D and C_A take constant values of 4·059, 0·427 and 1·733, respectively, the above relations explain 87, 92 and 99 per cent of the variances, respectively, for 529 field observations mostly from natural rivers. However, C_W, C_D and C_A are generally variable and, as analysed by Huang and Warner (1995), they physically relate to the critical shear force for the movement of bank material (an index of bank strength), τ_{cbk}, as follows:

$$C_W \propto \tau_{cbk}^{-\frac{5J}{8-5J}} \tag{4}$$

$$C_D \propto \tau_{cbk}^{-\frac{5J}{8-5J}} \tag{5}$$

$$C_A \propto \tau_{cbk}^{-\frac{5J}{8-5J}} \tag{6}$$

According to Huang and Warner (1995), J in Equations 4 to 6 is a constant between 0·25 and 0·35 and, theoretically, the following interrelations between C_D, C_A and C_W maintain:

$$C_D = C_W^{-0 \cdot 6} \tag{7}$$

$$C_A = C_W^{0 \cdot 4} \tag{8}$$

Equations 1 to 6 indicate clearly that a larger τ_{cbk} and thus a stronger bank results in a narrower but deeper and smaller channel section. On the other hand, a smaller τ_{cbk} and thus a weaker bank produces a wider, shallower and larger channel section.

Method

The main objective of this study is to determine the variations of coefficients C_W, C_D and C_A in Equations 1 to 3 for banks of different strength. Although Equations 4 to 6 define clearly how C_W, C_D and C_A are related to bank strength index τ_{cbk}, the determination of τ_{cbk} appears to be very difficult due to the complex and heterogeneous nature of bank sediment and bank vegetation (Thorne, 1982, 1990; Hickin, 1984; Gregory and Gurnell, 1988; Hupp and Osterkamp, 1996). On account of this we analyse observations available from several sources in

terms of the types of bank sediment and vegetation and then relate these to variations in C_W, C_D and C_A in Equations 1 to 3.

For convenience, Equations 1 to 3 are simply expressed as the following linear relations:

$$W = C_W W' \tag{9}$$

$$D = C_D D' \tag{10}$$

$$A = C_A A' \tag{11}$$

where

$$W' = \frac{Q^{0\cdot5} n^{0\cdot355}}{S^{0\cdot156}} \tag{12}$$

$$D' = \frac{Q^{0\cdot3} n^{0\cdot383}}{S^{0\cdot206}} \tag{13}$$

$$A' = \frac{Q^{0\cdot8} n^{0\cdot738}}{S^{0\cdot362}} \tag{14}$$

This means that, if field measured channel width (W), depth (D) and cross-sectional area (A) are plotted against parameters W', D' and A' computed according to Equations 12 to 14, there should be parallel but separate lines passing through each point and the intercepts will be the values of C_W, C_D and C_A for log–log analyses of Equations 9 to 11. As seen from Equations 4 to 6, C_W, C_D and C_A are bank strength indices and increasing bank strength results in smaller values of C_W and C_A but a larger value of C_D, and vice versa.

Data

Table I shows the data used in this study. These data are from several geographic regions and for different purposes they have been previously categorized into groups. However, some of them are reclassified in this study according to additional information available on bank sediment and bank vegetation in order to reflect more accurately the strength of banks.

Field data from 62 locations on stable gravel rivers in the United Kingdom and from 24 reaches of gravel-bed rivers in the Rocky Mountain region of Colorado were classified by Hey and Thorne (1986) and Andrews (1984), respectively, according to the character of bank vegetation. Due to limited variation in bank sediment, their classifications are surrogates for bank strength and therefore no further classification is made here.

Field data from 24 reaches of stable irrigation canals in the United States were previously subdivided by Simons and Albertson (1960) into four categories: sand bed and banks; sand bed and cohesive banks; cohesive bed and banks; and coarse non-cohesive banks. Clearly, this classification does not fully reflect the possible variation in bank strength. This study reclassifies the data according to the information provided by Simons and Albertson (1960) on both bank sediment and bank vegetation. Table II presents a detailed description of this new classification.

For field data from 30 sites on four small streams in southeastern Australia, Huang and Nanson (1997) provided quantitative indices of riparian vegetation and sediment for each site. As a result, five major categories of bank strength (three for gravel-bed channels and two for sand-bed channels) can be clearly defined (Table III).

Although all the data used in this study have been previously analysed, no uniform but only regional results have been achieved. While Hey and Thorne (1986) and Andrews (1984) identified that bank vegetation affects only channel width to a degree, the application of a more complex multivariate model by Rhoads (1992) to the

Table I. Data sources, bank types and indices of bank strength

Data source	Bank types*	Data sets	Bank strength indices†					
			C_W	σ_W	C_D	σ_D	C_A	σ_A
Gravel-bed rivers in the UK (Hey and Thorne, 1986)	A: Grassy banks	13	5·47	0·98	0·36	0·04	1·95	0·14
	B: 1–5% tree/shrub	16	4·34	0·42	0·41	0·02	1·78	0·07
	C: 5–50% tree/shrub	13	3·44	0·39	0·47	0·03	1·62	0·07
	D: >50% tree/shrub	20	3·23	0·43	0·49	0·04	1·58	0·08
Stable irrigation canals in the USA (Simons and Albertson, 1960)	A: Non-cohesive sand with light to moderate vegetation	6	6·11	0·58	0·36	0·02	2·04	0·08
	B: Moderately cohesive sand with light to moderate vegetation or non-cohesive sand with heavy vegetation	7	3·77	0·44	0·46	0·05	1·68	0·08
	C: Cohesive sand with light to heavy vegetation or moderately cohesive sand with heavy vegetation	8	3·70	0·38	0·45	0·02	1·67	0·07
	D: Unclear bank material	3	3·87	0·54	0·44	0·04	1·71	0·10
Gravel-bed rivers in the Rocky Mountain of Colorado, USA (Andrews, 1984)	A: Thin vegetation (sparse grass and some bushes)	14	5·61	1·02	0·36	0·04	1·96	0·14
	B: Thick vegetation (trees and dense bushes)	10	5·55	0·59	0·36	0·02	1·96	0·09
Gravel-bed channels in southeastern Australia (Huang and Nanson, 1997)	A: Non-vegetated banks	6	4·42	0·53	0·40	0·04	1·78	0·19
	B: Banks sparsely lined with large trees	6	2·99	0·69	0·57	0·07	1·67	0·28
	C: Banks densely lined with large trees	4	2.24	0.20	0.63	0.03	1.40	0.11
Sand-bed channels in southeastern Australia (Huang and Nanson, 1997)	D: Banks containing *c.* 20% silt and clay with moderate vegetation	8	5·03	0.39	0.39	0·02	1·93	0·10
	E: Banks containing *c.* 40% silt and clay with moderate vegetation	6	3·37	0·79	0·51	0·09	1·67	0·14

* More detailed description is presented in the text and Tables II and III.
† C_W, C_D and C_A are the averages for all the observations in each bank type and σ_W, σ_D and σ_A are their corresponding standard deviations.

data used by Hey and Thorne (1986) showed clearly that bank vegetation also affects channel depth. Although Simons and Albertson (1960) emphasized that the types of sediment on both channel bed and banks play a significant role in determining channel geometry, Huang and Nanson (1997) found that not only sediment composition but also the location, size and density of riparian vegetation have an effect on channel geometry. Most importantly, the studies of Rhoads (1992) and Huang and Nanson (1997) revealed the limited value of using flow discharge and vegetation or sediment as the only independent variables to identify the general role of vegetation or sediment in influencing river channel geometry. For that reason a more complex multivariate model that is physically based and has been proven to be of general use is applied here.

DATA ANALYSIS

With the data described in Table I, the values of W', D' and A' for each observation are computed using Equations 12 to 14, as are the values of C_W, C_D and C_A using Equations 9 to 11. For each group of data categorized in terms of the character of bank sediment and bank vegetation, Table I gives the *average* values of bank strength indices (averages of C_W, C_D and C_A) and their corresponding standard deviations (σ_W, σ_D and σ_A) for all of the observations in each group. In general, Table I shows that different bank types show strength

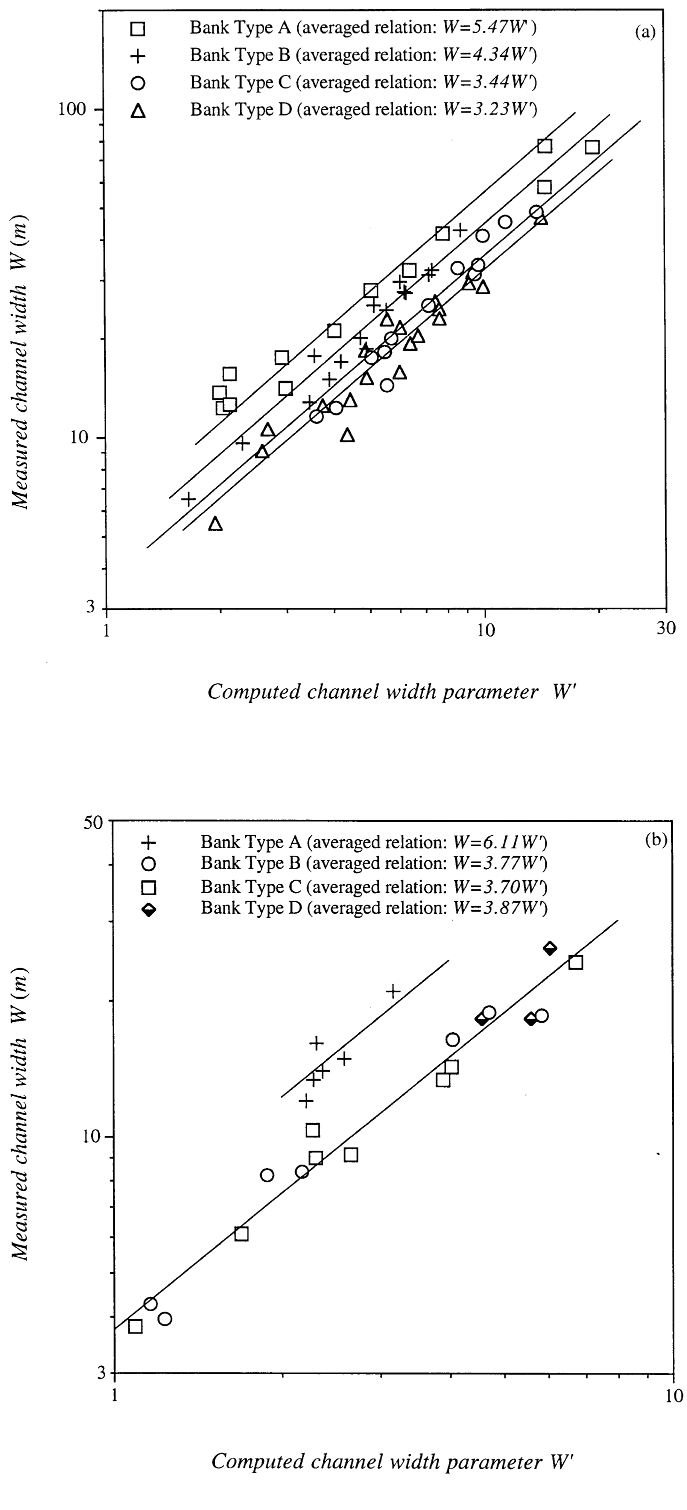

Figure 1. Variations of C_W for different bank types. (a) Gravel streams in the UK studied by Hey and Thorne (1986) (lines are drawn with coefficients averaged from associated groups of points). (b) American irrigation canals studied by Simons and Albertson (1960) (two lines are drawn with coefficients averaged from all Type A channels and the combination of all Type B, C and D channels, respectively).

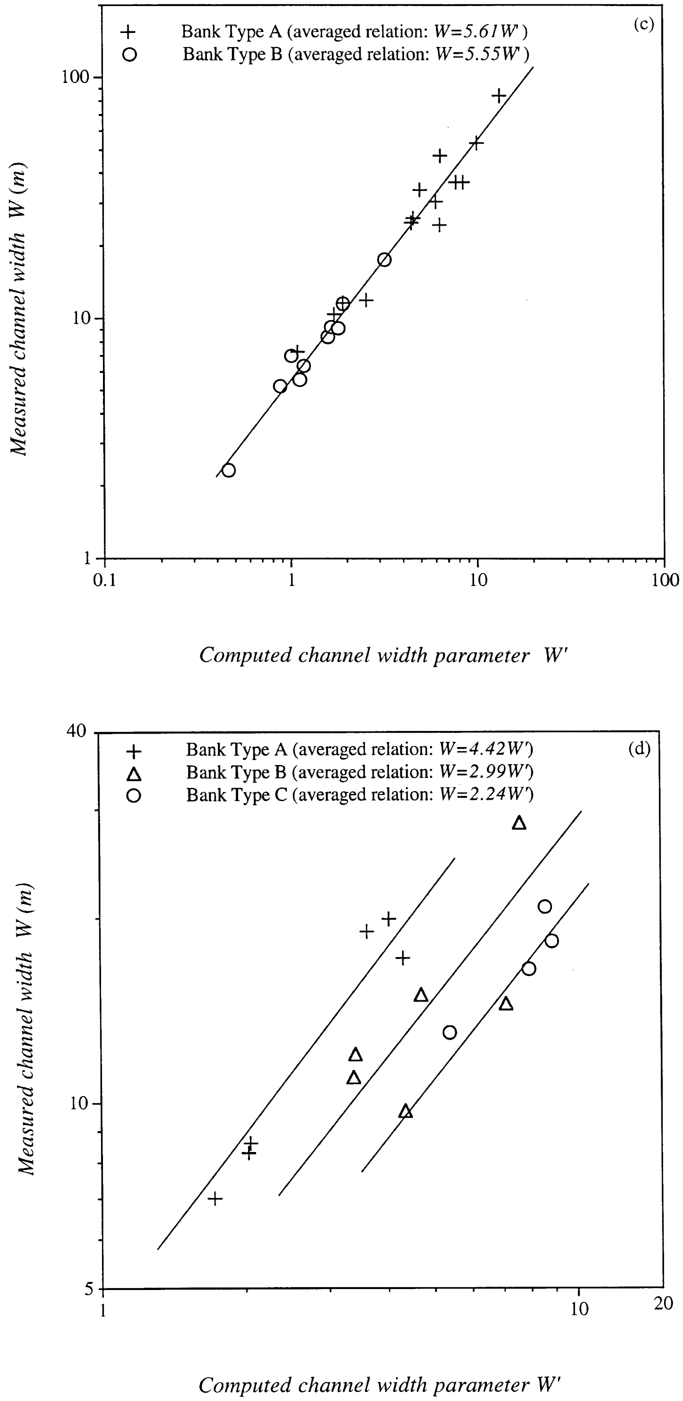

Figure 1. Variations of C_W for different bank types. (c) Gravel-bed rivers on Colorado studied by Andrews (1984) (line is drawn with coefficient averaged from all of Type A and B channels). (d) Gravel-bed channels in southeastern Australia studied by Huang and Nanson (1997) (lines are drawn with coefficients averaged from associated groups of points).

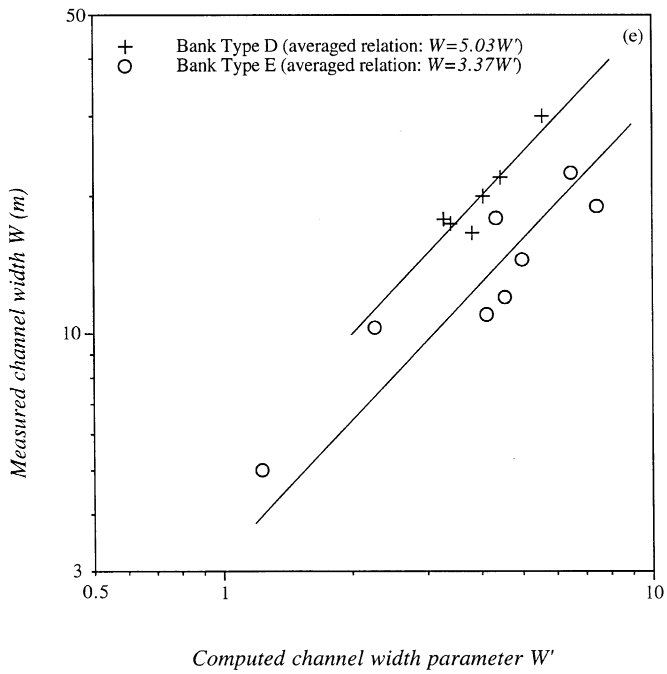

Figure 1. Variations of C_W for different bank types. (e) Sand-bed channels in southeastern Australia studied by Huang and Nanson (1997) (lines are drawn with coefficients averaged from associated groups of points).

Table II. Reclassification of Simons and Bender data according to the information provided by Simons and Albertson (1960)

No.	Extent of bank vegetation	Bank sediment	Channel side material d_{50} (mm)	Bank type*
1	Moderate	Moderatley cohesive	0·207	B
2	Light	Moderately cohesive	0·133	B
3	Light	Cohesive	0·087	C
4	Light	Cohesive	0·0515	C
5	Light	Cohesive	0·0419	C
6	Light	Cohesive	gravel	D
7	Moderate	Cohesive	0·0806	C
8	Light	Non-cohesive	0·098	A
9	Light	Non-cohesive	0·098	A
10	Light	Non-cohesive	0·143	A
11	Light	Non-cohesive	0·166	A
12	Light	Gravel	0·109	D
13	Light	Gravel	0·060	D
14	Light	Moderately cohesive	0·149	B
15	Light	Moderately cohesive	0·074	B
16	Moderate	Moderately cohesive	0·079	B
17	Moderate	Moderately cohesive	0·077	B
18	Heavy	Moderately cohesive	0·182	C
19	Moderate	Moderately cohesive	0·286	B
20	Heavy	Cohesive	0·036	C
21	Heavy	Cohesive	0·034	C
22	Moderate	Non-cohesive	0·177	A
23	Light	Non-cohesive	0·271	A
24	Heavy	Non-cohesive	0·067	B

* Detailed information on bank types:

- A Non-cohesive sand with light to moderate vegetation
- B Moderately cohesive fine sediment with light to moderate vegetation, or non-cohesive sand with heavy vegetation
- C Cohesive fine sediment with light to heavy vegetation, or moderately cohesive fine sediment with heavy vegetation
- D Bank material unclear (here Simons and Albertson's (1960) description of bank sediment and channel side material are inconsistent. For example, Channels 12 and 13 identify bank sediment as gravels but the median sizes of channel side material are given as <0·11 mm).

Table III. Detailed information on bank types of Huang and Nanson's (1997) data

Bank type	Bank vegetation*	Bank sediment
A: Non-vegetated banks		Gravel
B: Banks sparsely lined with large trees	TH>6 mm; TF<5; BHD=19–40 cm	Gravel
C: Banks densely lined with large trees	TH>6 mm; TF>5; BHD=21–33 cm	Gravel
D: Banks of *c.* 20% silt and clay with moderate vegetation	TH>6 mm; TF=1·1–2·6; BHD=9–19 cm	Fine sediment on average containing *c.* 40% silt and clay (mostly clay)
E: Banks of *c.* 40% silt and clay with moderate vegetation	TH>3 mm; TF=2·7–3·1; BHD=13–22 cm	Fine sediment on average containing *c.* 40% silt and clay (mostly clay)

* TH = tree height; TF = tree frequency (average number of trees per 10 m of bank length; BHD = average breast height diameter of trees; the roots of all the trees penetrate to the toe of banks.

differences in their different values of bank strength indices (averages of C_W, C_D and C_A for each group of data). In some cases, however, the averages of C_W, C_D and C_A for several bank types show only slight or non existent differences. Examples of this in Table I are Type B, C and D channels in the American stable irrigation canals studied by Simons and Albertson (1960) and the two types of channels in the gravel-bed rivers defined by Andrews (1984).

Figure 1 is plotted with all of the data described in Table I and shows how coefficient C_W varies with different bank types via W and W' relationships. Those relations for coefficients C_D and C_A are not presented because they are less sensitive to the changes in bank type as illustrated in Equations 4 to 8. Although an attempt is made to plot all the average relations between W and W' for all the types of banks, some of the relations for several bank types are too close to be distinguished in the figure because their intercepts (the average values of C_W, C_D and C_A) have very similar or equal values. Therefore, those bank types with very similar average values of C_W are presented just as a simple set and the intercepts of the lines drawn in Figure 1b and 1c are the values of C_W averaged from all the associated bank types (note, these lines are not regression lines although they do fit their associated fields of points fairly well).

As seen in Figure 1, each group of data is scattered and due to the complexity of bank sediment composition and bank vegetation some of the data overlap with those from other groups. It is also this complexity that makes American stable irrigation canals show only two distinctly different groups of strength indices within the four bank types (Figure 1b and Table I) and the gravel-bed rivers defined by Andrews (1984) show only one group of strength indices (Figure 1c and Table I). These insensitive relationships between bank types and strength indices may also result from the method used to categorize these data. Due to the lack of quantitative information on bank vegetation and sediment, a simple qualitative approach has been used to subdivide the data provided by Simons and Albertson (1960) and Andrews (1984) in Figure 1b and 1c. On the contrary, a quantitative approach based on very detailed quantitative indices of bank vegetation and sediment illustrate clear one-to-one relationships between bank types and strength indices as seen in Figure 1a, 1d and 1e for the data provided by Hey and Thorne (1986) and Huang and Nanson (1997).

A summary of all the results obtained here appears to give logical predictions of the influence of commonly occurring bank conditions on bank strength. The densely vegetated banks are normally the strongest in resisting erosion and thus exhibit the smallest values of C_W and C_A and the largest values of C_D [values of 3·23 for C_W, 0·49 for C_D and 1·58 for C_D for Type D channels (>50 per cent tree/shrub) in gravel rivers in the UK, as shown in Figure 1a and Table I, and values of 2·24 for C_W, 0·63 for C_D and 1·40 for C_A for Type C channels (banks densely lined with large trees) in gravel-bed rivers in southeastern Australia as shown in Figure 1d and Table I]. In contrast, non-cohesive sand banks with light to moderate vegetation are normally the weakest in resisting erosion (Type A channels in American stable irrigation canals) and thus exhibit the largest values of C_W and C_A and the smallest value for C_D (values of 6·11 and 2·04 for C_W and C_A, and a value of 0·36 for C_D; Figure 1b and Table I). Gravel banks and banks with moderately cohesive fine sediment covered with moderately dense

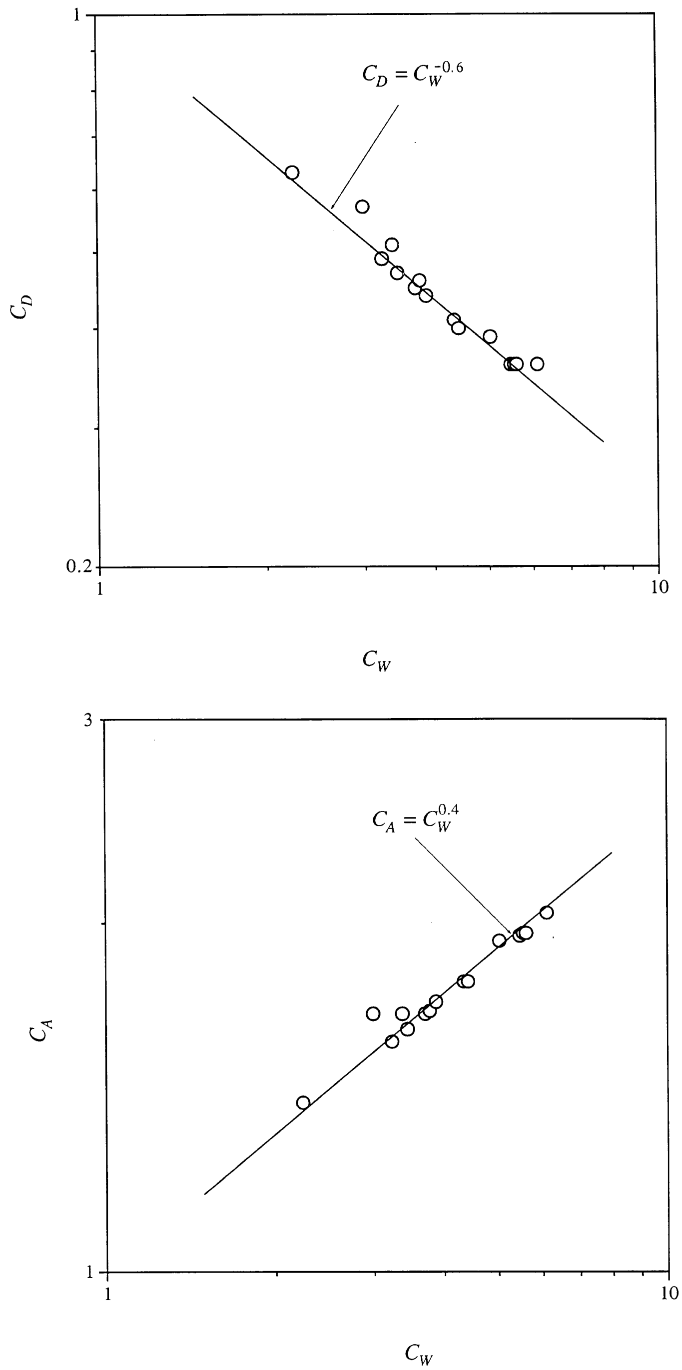

Figure 2. Relationships of C_D and C_A with C_W

vegetation have medium values of bank strength that are reflected in the values for C_W, C_D and C_A (Figure 1 and Table I).

On the other hand, although the values of C_W, C_D and C_A for each type of bank presented in Table I are averaged from all the plots, Figure 2 shows that the theoretical relations illustrated in Equations 7 and 8 fit these

Table IV. Gross ranges of variation in C_W for various bank types

Bank type	C_W
Banks with non-cohesive sand	6·0–6·25
Gravel banks	4·5–6·0
Banks with moderately cohesive sand	3·5–5·0
Banks with highly cohesive sand	2·5–3·5
Moderately vegetated and moderately cohesive sand banks	3·0–4·0
Heavily vegetated and highly cohesive sand banks	2·1–3·0

averaged values almost perfectly. This observation provides further support for the quantitative results obtained here.

Due to the complex nature of bank strength and the limited data analysed, Table IV presents only a summary of the gross ranges of variation in C_W for commonly occurring bank conditions according to the results presented in Figure 1 and Table I. This is because C_W, as the coefficient most responsive to bank strength, can be relatively accurately determined. Once it is determined, C_D and C_A can then be computed from Equations 7 and 8.

DISCUSSION

From Figure 1 and Tables I and IV, it is apparent that C_W varies about three-fold (2·1 to 6·25) and consequently it can be determined from Equations 7 and 8 that C_D varies about two-fold and C_A about 1·6-fold. This means that the influence of bank strength on channel width is generally considerably more than on depth and cross-sectional area. This may explain why most empirical studies, such as those by Andrews (1984), Hey and Thorne (1986) and Huang and Nanson (1997), can identify only the effect of bank strength on channel width. However, it is apparent in Equations 4 to 6 that this variation in C_W results from very large changes in bank strength of about two orders of magnitude (provided that J maintains a constant 0·3 as suggested by Huang and Warner, 1995). Consequently, although bank strength might increase by an order of magnitude or more due to bank vegetation (e.g. Carson and Kirkby, 1972; Smith, 1976; Kirkby and Morgan, 1980; Thorne, 1990), its influence on river channel geometry is not of that proportion. In fact, bank strength appears to have a relatively limited impact compared to flow discharge and as a consequence, the bivariate relations between hydraulic geometry and flow discharge have been readily and widely identified (e.g. Lacey, 1930, 1935; Blench, 1952; Leopold and Maddock, 1953; Park, 1977; Rhodes, 1987).

CONCLUSIONS

Although there are problems in providing accurate predictions of bank strength in river channels, Huang and Warner's (1995) multivariate model of channel geometry allows the influence of bank strength on alluvial channel geometry to be broadly quantified and predicted in terms of the character of bank sediment composition and bank vegetation.

A large range of field observations collected from several sources in several countries are examined here and categorized in terms of bank character, and the quantitative influence of bank strength on channel geometry is analysed in an integrated way. It is demonstrated clearly that both bank sediment and bank vegetation play an important role in influencing alluvial channel geometry, even in the relatively simple case of stable canals where the influence of bank vegetation has long been ignored.

The results obtained in this study show quantitatively that bank strength exerts a significant influence on channel width with less influence on depth and cross-sectional area. Within the range of the data analysed here, bank strength can produce a three-fold change in channel width, about a two-fold change in depth, and only about a 1·6-fold change in cross-sectional area.

Furthermore, this study suggests that a detailed quantitative analysis of the size, density, location and even health of bank vegetation could be of great help in providing a high level of prediction for bank strength.

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